The Design and Production of the Higher-Order-Mode Loads for CEBAF*

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Abstract

At CEBAF, 676 Higher-Order-Mode (HOM) loads are being installed, within the beam vacuum at 2 K, to damp HOM's that affect the stability of the recirculating electron beam. In this paper, the requirements imposed on the loads and the microwave absorbing material comprising them are discussed together with an analysis of their performance and effect on some relevant modes.

I. INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) will provide by design an electron beam of 200 μA with an energy as high as 4 GeV. This performance is achieved by recirculating the electrons up to five times in two antiparallel linear accelerators which make use of niobium superconducting cavities resonating at 1497 MHz and kept at 2 K. When cold, the vacuum in the cavities is better than 10^{-10} torr. Any component that is placed within the accelerator must satisfy a number of environmental constraints designed to prevent surface contamination of the superconducting cavities or excessive heat dissipation on the part of the fundamental mode which must have an unloaded Q of at least $2.4 \cdot 10^9$ at 5 MV/m. Under normal operating conditions only tens of milliwatts of HOM power per cavity are expected making it thermodynamically advantageous to keep the loads at 2 K.

The electrical properties of the HOM loads must be such that they provide return losses of about 10 dB, in the special size HOM rectangular waveguide (1.500" × 3.110"), from 1.9 GHz (the waveguide cutoff) up to 10 GHz and beyond, in all the possible waveguide modes and at any frequency in that range [1]. This requirement translates into damping some of the modes from Q's potentially in the 10^9–10^{10} down to the 10^2–10^3 level.

The HOM loads developed for CEBAF provide the proper attenuation by using a compact yet broadbanded design [2]. This design incorporates an absorbing material developed specifically for this application which shows dielectric properties independent of temperature [3] and high thermal conductivity [4]. This makes it an ideal material for several accelerator applications [5].

II. LOAD DESIGN

A. Geometry

The cutoff frequency of the HOM waveguides is 1.9 GHz for the TE_{10} mode. Above 3795 MHz, additional modes (TE_{20}, TE_{01}, TE_{11}, TM_{11}, etc.) propagate in the guide, contributing to the extraction of the HOM power. Since the best matching of a dielectric absorber to the electromagnetic waves occurs at locations where the electric field is lowest, the design of the load is such that its leading edge is as close as possible to the corner where the electric field is zero for all TE waveguide modes which dominate the HOM power extraction at the lower and most critical frequencies (Figure 1). With this geometry a very compact loads design is achieved (Figure 2) which can be assembled in a few economical manufacturing steps.

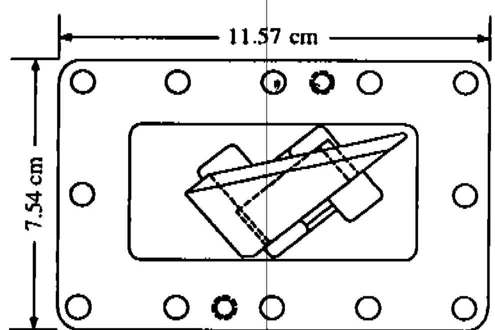

Figure 1. CEBAF's HOM load assembly. The geometry is designed to effectively match to several waveguide modes and over a broad frequency range.

Figure 2. The CEBAF HOM load assembly, with the stainless steel flanges and the brazed lossy ceramic parts. The load is only 7 cm long, thanks to the high dielectric constant of the absorber material.

B. The Material

A totally new ceramic material had to be developed to provide temperature-independent absorption down to 2 K. The ceramic composite is based on the artificial dielectric model [6][7]. It consists of a mixture of aluminum nitride (a matrix which provides good strength and high thermal conductivity, ≥60–80 W/[m·K] [4]) with glassy carbon spheres of 3–12 μm diameter which dissipate most of the microwave power

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(Figure 3). Glassy carbon is an amorphous form of carbon produced by pyrolysis of phenolic resins [8]. The material is hot pressed [9] to achieve full density vacuum compatibility.

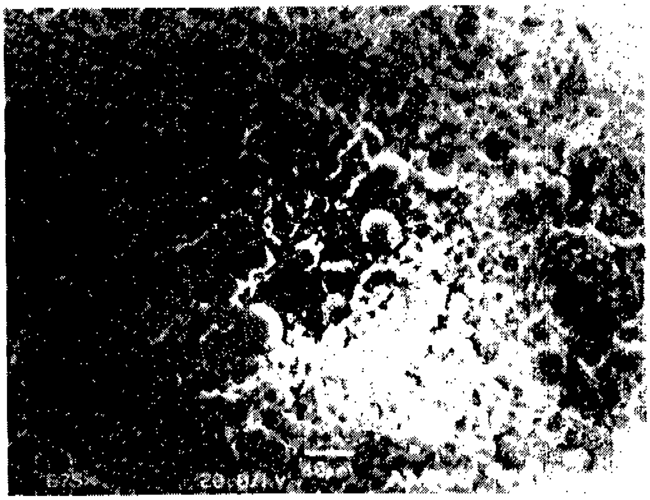

Figure 3. SEM image of the ceramic artificial dielectric used in the construction of CEBAF's loads. Note the glassy carbon spheres embedded in the aluminum nitride ceramic.

The relative dielectric constant needed to meet CEBAF's requirements was determined to be in the range 20–30, with a loss tangent greater than 0.1, over the frequency range of 1 to 6 GHz [10]. The dielectric constant and the loss tangent of the AlN-glassy carbon composite as a function of frequency were measured at room temperature using a Hewlett-Packard dielectric probe HP85070A in conjunction with a HP8753C network analyzer (Figure 4)[11]. Dielectric and magnetic properties to 20 GHz were measured by Hartung [12]. His data show that the losses have no magnetic component and that the dielectric loss tangent increases monotonically to higher frequencies.

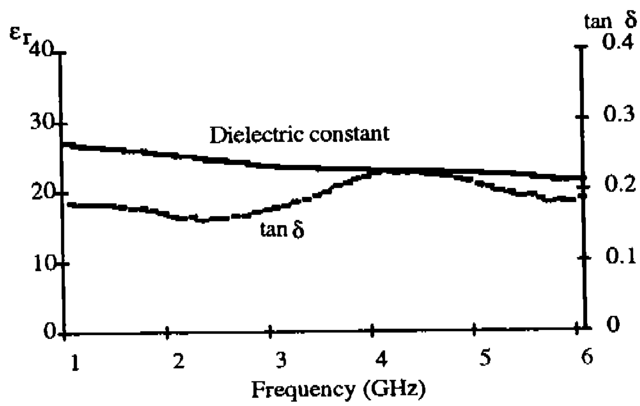

Figure 4. Dielectric constant and loss tangent of AlN loaded with glassy carbon. AlN alone has a dielectric constant of about 8 and a loss tangent < 10^{-4} at room temperature.

Measurements of the loads' return losses at any temperature between 1.5 and 300 K show that the dielectric properties of the material are independent of temperature in that range (Figure 5). This independence was corroborated by direct measurement of HOM's Q's at low temperature.

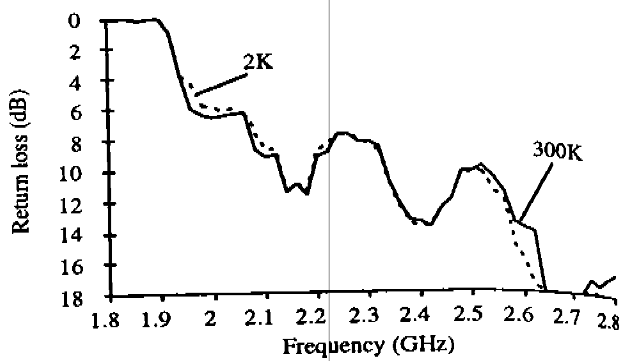

Figure 5. Return loss of AlN glassy carbon measured at 2 K and at room temperature.

III. PRODUCTION

A. Production Components and Assembly

Most of the fabrication steps for the production of the HOM loads were developed at CEBAF and several assembly procedures were performed in the laboratory to guarantee uniform quality and control of production parameters.

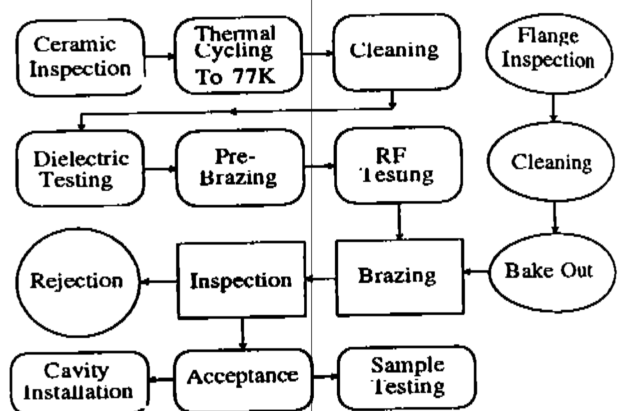

Figure 6. Flow chart of the production process. At any step before the final braze, parts can be rejected and/or reworked without major loss of added value. A fraction of the accepted loads undergoes more severe tests.

The ceramics are manufactured by industry [9] as hot-pressed tiles which are tested prior to cutting and approved for compliance with the above dielectric properties' ranges. The ground parts are again tested with the dielectric probe to ensure repeatable microwave performance. Approved ceramic parts are brazed together in high vacuum with Ticusil® (Wesgo), and the load's return losses measured before final brazing to the support flange. The temperature ramp rate to and from the melting point of the alloy (830 °C) is controlled to avoid thermal stresses to ceramic material.

The 316L stainless steel flange with 16 μin electropolished surface finish provides a backing for the indium seal. A copper support is brazed to the stainless steel flange. The copper part prevents excessive stresses at the ceramic-to-metal braze. In other applications, this copper support can also be thermally grounded either to the helium bath or to other heat sinks to remove larger amounts of dissipated power.

Flange inspections ensure that the surface finish requirement of 16 μin, or better, is consistently met at the indium sealing surface area. The flange surface is also visually inspected for stains, scratches, machining marks, pits, and other imperfections which could lead to unreliable vacuum seals and/or possible surface contamination of the cavities. Any surface irregularity within the sealing surface is cause for flange rejection. Special care is also taken to measure the dimensions of the copper insert in the flange. Tight dimensional tolerances are required to make the ceramic-copper braze structurally strong and insensitive to the thermal cycling.

As Figure 2 shows, the load consists of two ceramic parts. Every ceramic piece is inspected for dimensional tolerances as well as for the presence of any visible flaws such as chips, laminations, cracks, or inclusions. Ceramic parts are then thermally shocked three times by submersion into liquid nitrogen to test the structural integrity of the material.

Return loss measurements are performed on the brazed ceramics at room temperature using a single test flange. The final braze of the ceramics to the flange is performed after the return loss measurement to eliminate the possibility of damaging a cleaned flange during RF testing.

A comprehensive final inspection is performed on each load prior to cavity installation. Under current production procedures, the load acceptance rate is greater than 95%. Five percent of the accepted loads undergoes subsequent testing of RF, vacuum, and mechanical properties at cryogenic temperature. These test loads are not installed in the accelerator, because some of the tests can potentially damage the indium seal surface or the ceramic-to-metal joint integrity. Lifetime thermal cycling tests have indicated that the loads can withstand and exceed the equivalent of 20 years of operation thermal cycling in the accelerator environment.

B. Uniformity and Production Experience

In excess of 1200 AlN-glassy carbon ceramic parts have been processed and have undergone extensive testing and inspections and have been utilized in the construction of more than 600 HOM loads. Although occasional deviations from specifications have been observed, the production has proceeded with consistent results.

Variations in dielectric constant of the ceramic composite over the production have ranged, depending on the glassy carbon lot, over ± 5% within a given lot and by as much as ± 10% from lot to lot. The latter variation seems to be also associated with minute density differences of the ceramics. Lot-to-lot variations can be compensated for by adjustments in the concentration of the glassy carbon (by as little as 0.1% by weight). This control on the dielectric constant is a primary advantage of artificial dielectric composites and makes it possible to consistently maintain this parameter over large production quantities.

Most of the ceramic material manufactured by Ceradyne meets and exceeds the UHV standards needed for installation in the superconducting cavities. One batch of ceramics manufactured from a specific glassy carbon lot yielded parts with slightly lower density (less than 1% lower) but with notably higher baseline pressure (Figure 7). By standard thermogravimetric analysis of the glassy carbon powders prior to hot pressing it is however possible to select lots which predictably provide parts with full density and extremely low outgassing rates (less than 10^{-11} torr liter/[s·cm^2]).

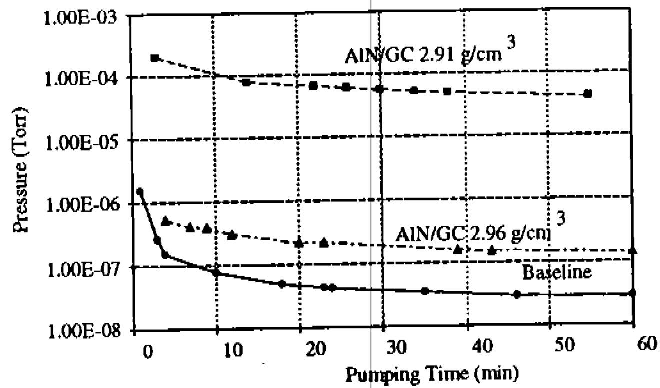

Figure 7. Comparison of vacuum pump-down times for two lots of ceramic parts. Different densities correspond to different lots of glassy carbon powders.

IV. CONCLUSIONS

The HOM loads developed at CEBAF provide damping of higher-order modes at any temperature between 1.5 K and room temperature and are compatible with the accelerator ultra-high vacuum. The reproducibility of their properties leads to dependable and well-controlled production. The special characteristics of the ceramic composite developed for the CEBAF HOM loads make it an ideal material in other applications where vacuum-compatible, temperature-independent, high thermal conductivity materials are needed.

V. ACKNOWLEDGMENTS

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